Physics of semiconductor detectors operation at low temperatures

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Outline

1. General on semiconductor detectors
2. S/B and P-I-N detectors
3. Radiation effect in detectors
4. Diamond properties
5. Trapping time degradation in Diamond and Silicon
6. Signal amplitude in Diamond and Silicon detectors
7. Conclusions

Back ground of PTI group which has been used in this presentation

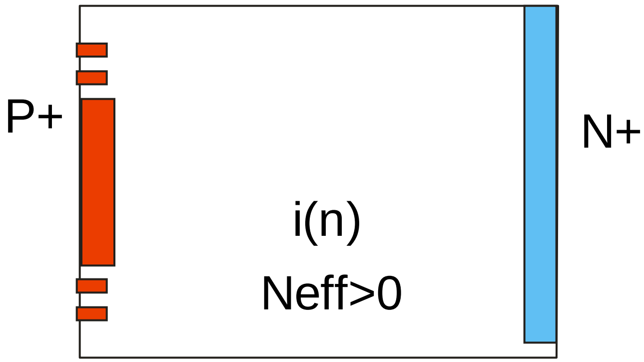
Ferformed R&Ds supported by international grants

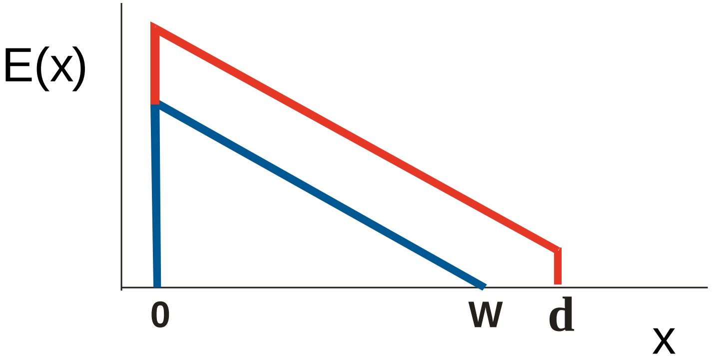
1. CAST: R&D of Transient Current Technique for radiation hard detectors study (BNL).
2. ISTC: R&D of silicon detectors array for medical application (USA, for-profit company)
3. INTAS: R&D of radiation hard cryogenic silicon detectors (CERN-RD39 collaboration).
4. INTAS: R&D of silicon strip detectors for ATLAS upgrade (CERN-ATLAS).
5. INTAS: R&D of radiation hard edgeless detectors for TOTEM (CERN-TOTEM).
6. INTAS: R&D of spectrometric DSSDs for EXL (NuSTAR, FAIR).

Development and Fabrication of Si detectors in the frame of international projects

- Current injected detectors for CERN-RD39 collaboration.
- P-on-N detectors for "TECHNOTEST" project of CERN-RD50 collaboration
- Reference P-on-N baby detectors for CERN-ATLAS strip detectors QA.
- Full set of edgeless detectors for CERN-TOTEM experiment.
- New : pre-series run of radiation hard silicon edgeless detectors for CERN-TOTEM upgrade.
- Si strip spectrometric detectors for NuSTAR experiment in FAIR program (GSI)

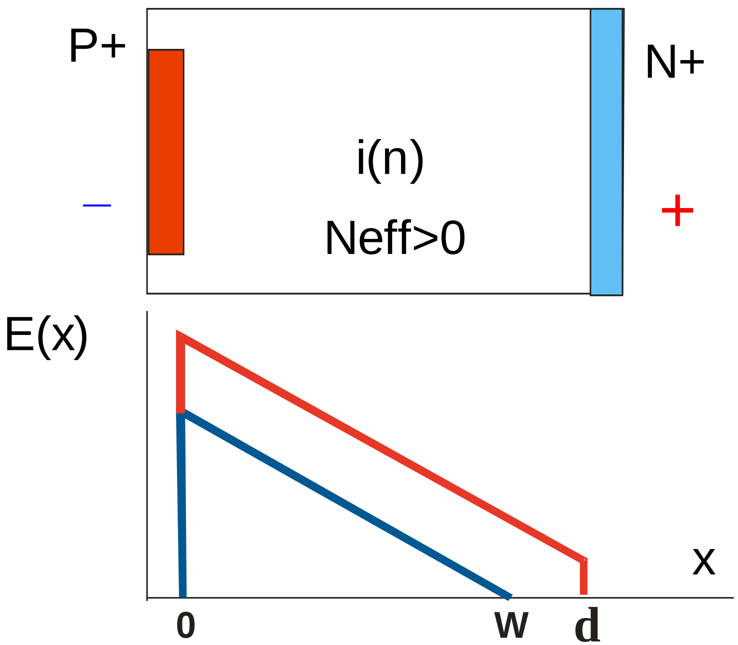
Si planar detector, static

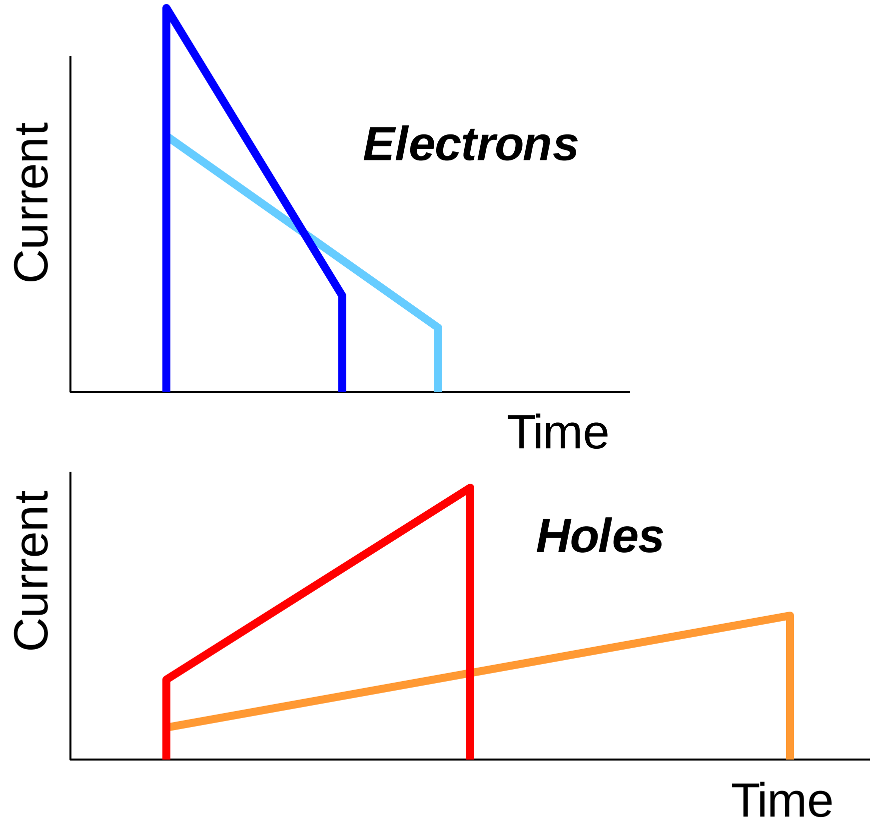




Electron mobility …1500cm²/v s
Hole mobility ……… 450cm2/v s
V_{sat}……………………1 10⁷cm/s
d ………………………300mkm
N_{eff} ……………………1 10^{12}cm^{-3}
V_{fd}……………………30-100 V
V_{op}……………………100-300V
<E>……………………1 10^4 v/cm

Si PAD detector response





$J = 1/d \times q\, \mu\, E$

Drift time …3 – 50ns

TCT data (830 nm laser)

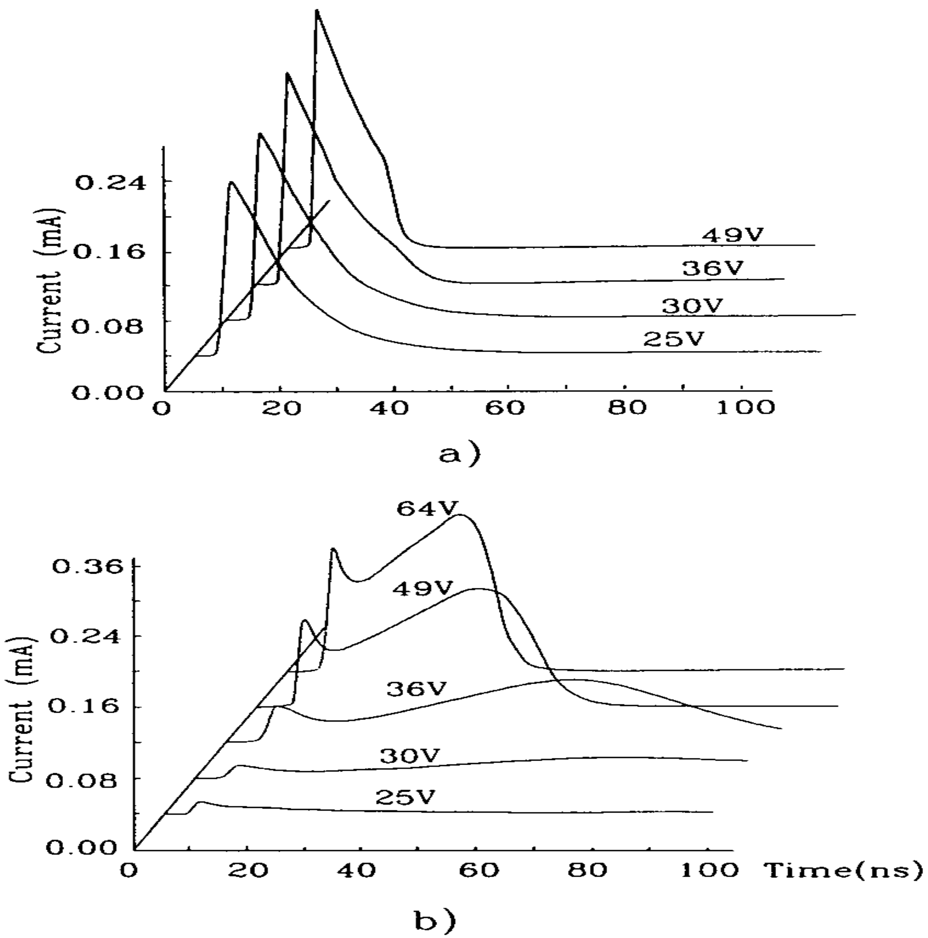
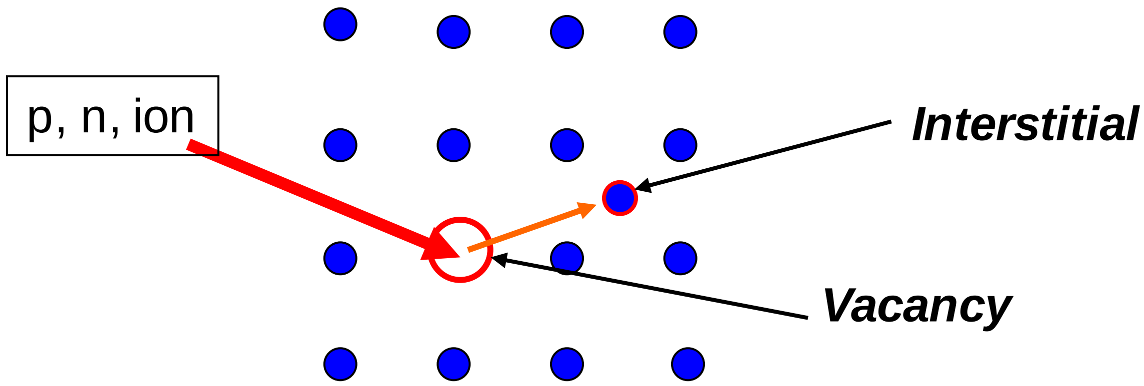


Fig. 9. A set of current pulses before and after depletion voltage for a deep level free detector: non-equilibrium carriers are generated (a) near the front p^+-contact (drift of electrons); (b) near the back n^+-contact (drift of holes).

V, Eremin, PTI, BLM, Oct 2011

Effect of irradiation on detector



Primary defects (Frenkel pairs): **vacancy (V)** and **interstitial (I)**

Secondary defects:

Divacancy - V + V
A center – V + O
E center - V + P

Life time degradation in Si

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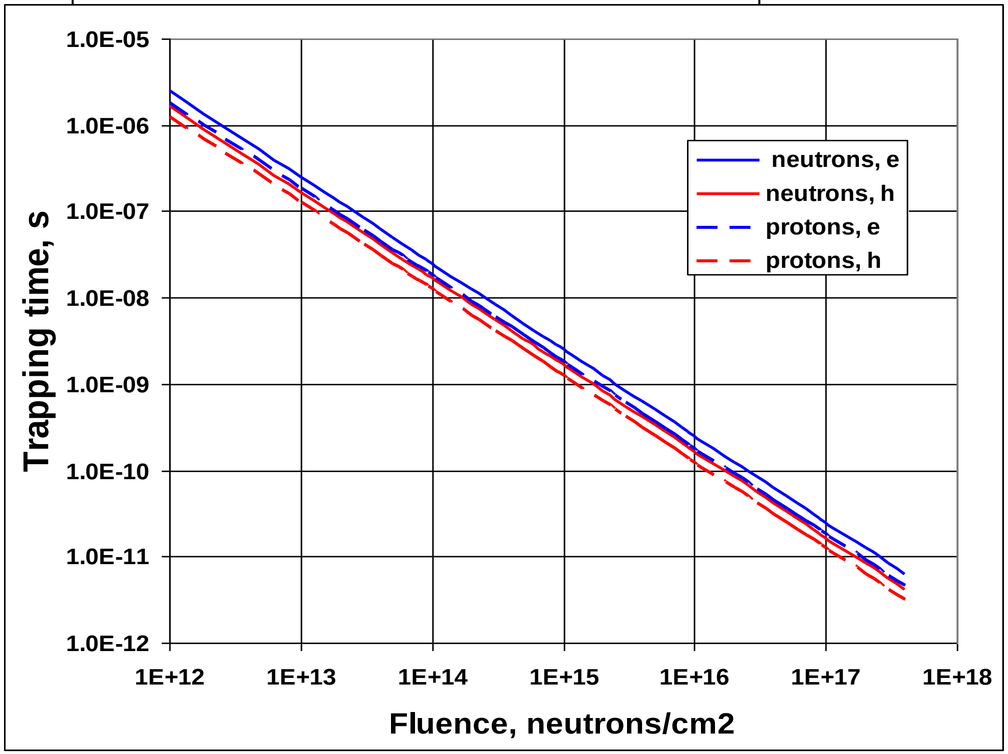
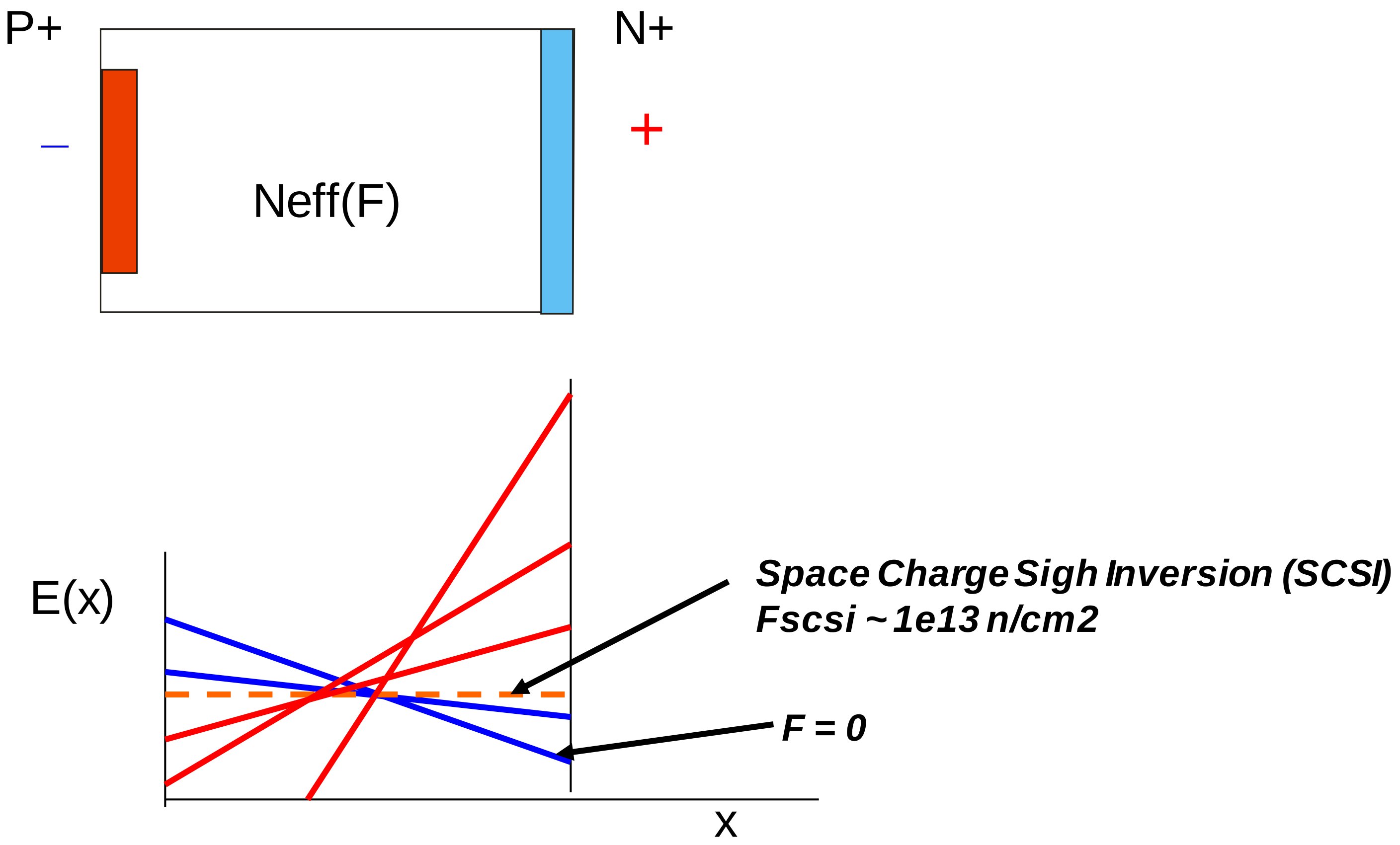


$$\tau(\phi) = (1/\tau_0 + \beta\phi)^{-1}$$

Trapping probability (protons)	
τ_e0	$1x10^3$
β_e	$5.5x10^3$
τ_h0	$1x10^3$
β_h	$8x10^3$

Electric field evolution in Si detectors with fluence (simple model)



Basic formulas

- Charge Collection Distance (CCD)

$$CCD = V_{dr} \times \tau_{tr}$$

- Trapping time

$$\tau_{tr} = (\sigma \times V_{th} \times N_{tr})\text{^-1}$$

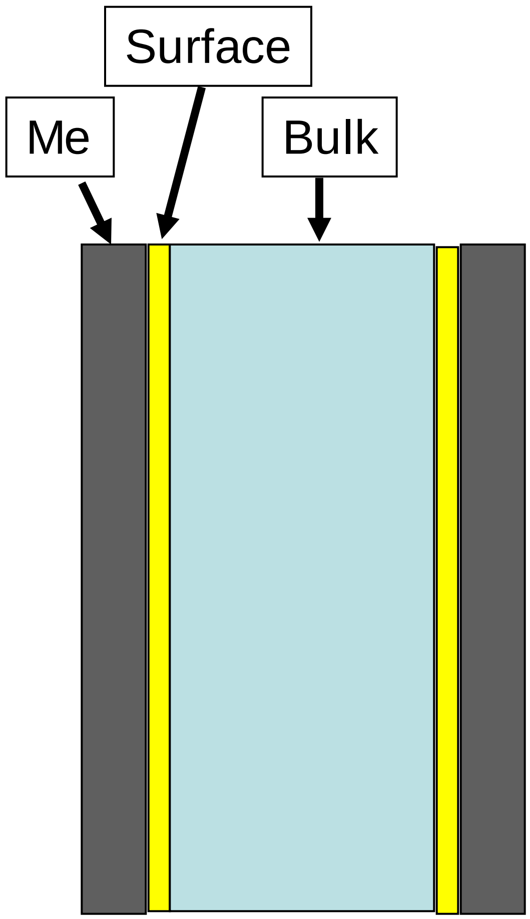
- *Detrapping time*

$$\tau_{dtr} = [(\sigma \times V_{th} \times N_c \times exp(-E_{act}/kT)]\text{^-1}$$

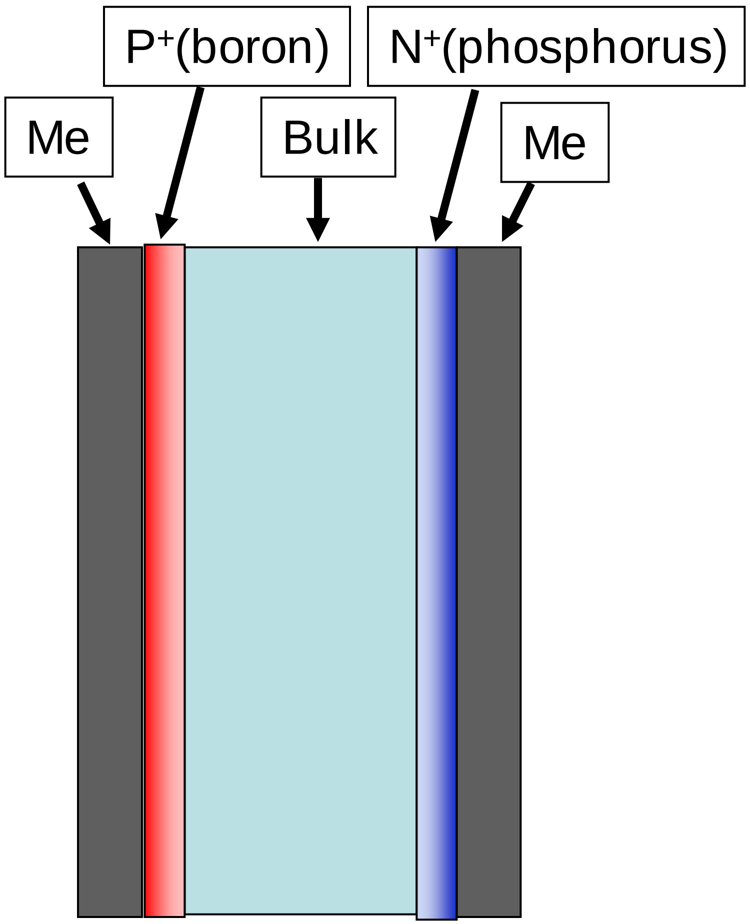
- *Width of the depleted layer in P-N junction*

$$W = \left(\frac{\varepsilon \varepsilon_o \cdot V}{2\pi q_e^2 N_{eff}} \right)^{\frac{1}{2}}$$

Comparison of Surface-barrier and P-I-N detectors

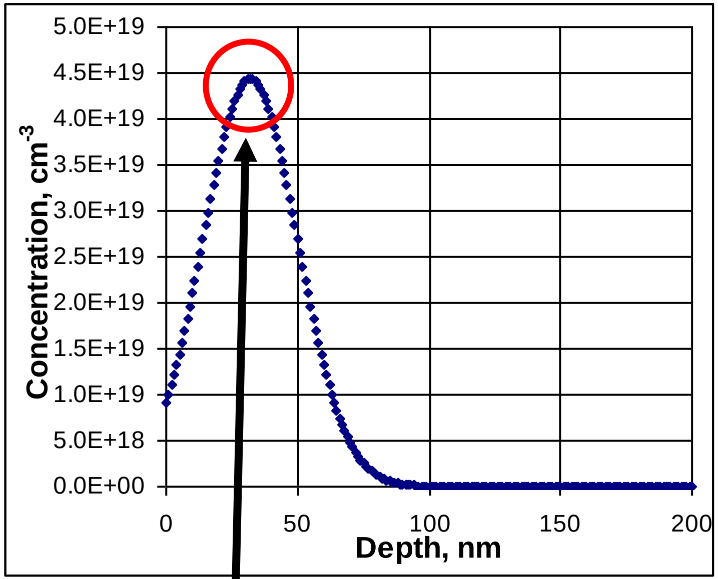


S/B detector
or M-S-M

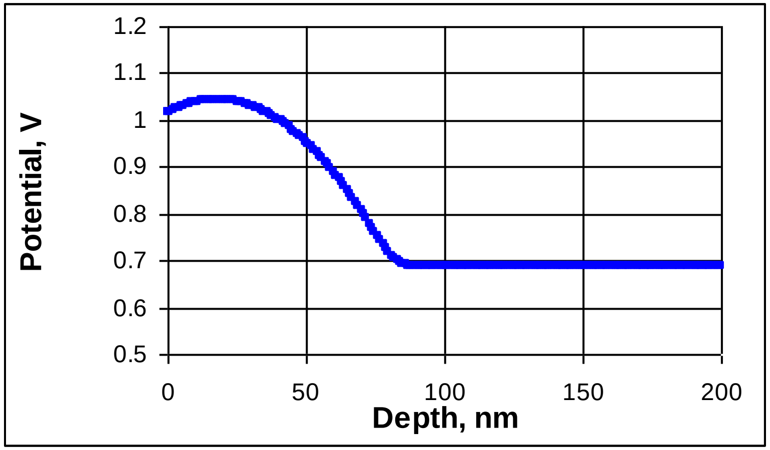


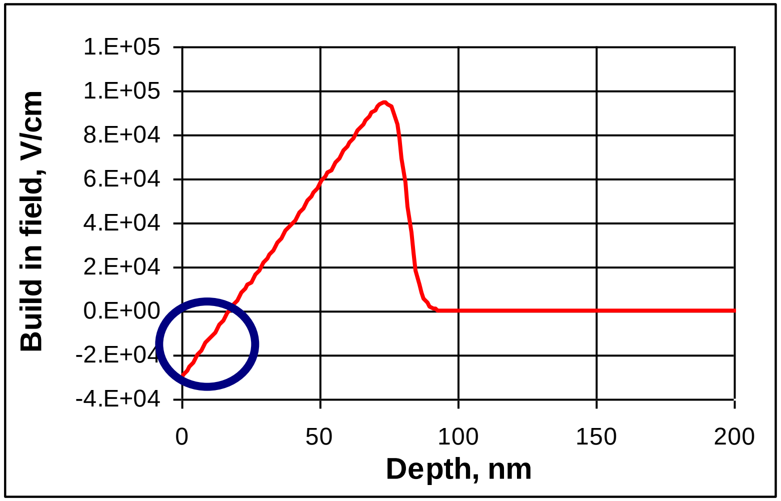
P-I-N

Electric field and potential at the detector entrance window



Degenerate Silicon
Si=Me





Comparison of S/B and P-I-N detectors

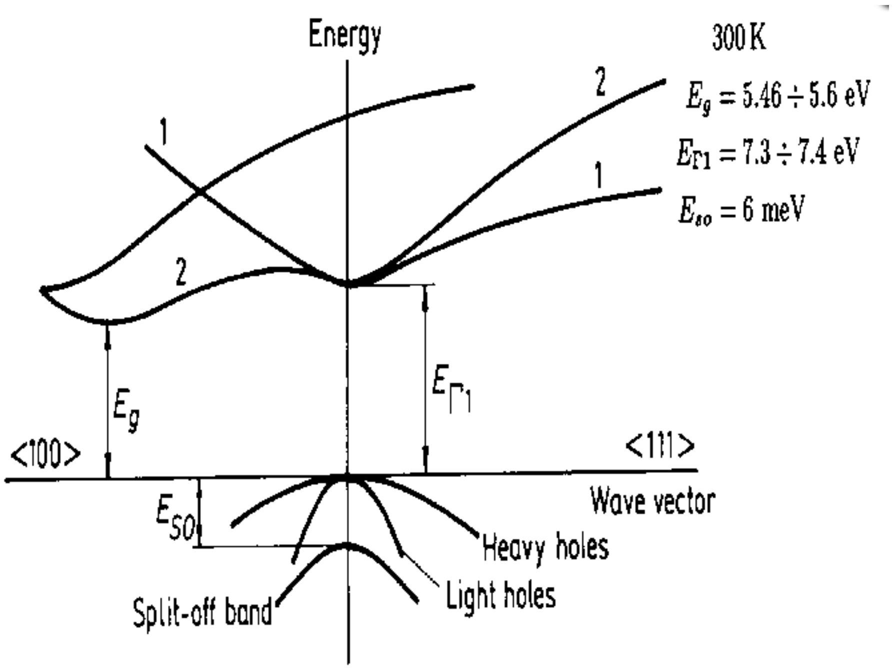
S/B

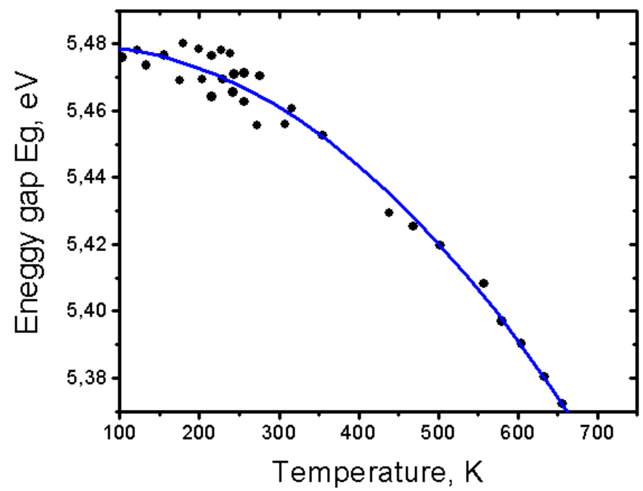
- Hardly controlled surface properties,
- Low reproducibility of S/B contact,
- Complicate technology,
- Oxidized surface or damaged interface prevents charge flow from the bulk to metal contact,
- High probability for charge accumulation at the interface and detector polarization,
- Unpredictable scenario of long term detector stability,
- Problem for operation at high current density,
- Optimal for low T operation in case the mentioned above problems will be solved.

P-I-N

- Reproducible technology,
- Smooth transition between bulk and me contact
- No interface between Si and Metal contact
- No chance accumulate charge at the surface
- No polarization,
- Requires more study for low T operation mainly for highly doped regions.

Band diagram for Diamond



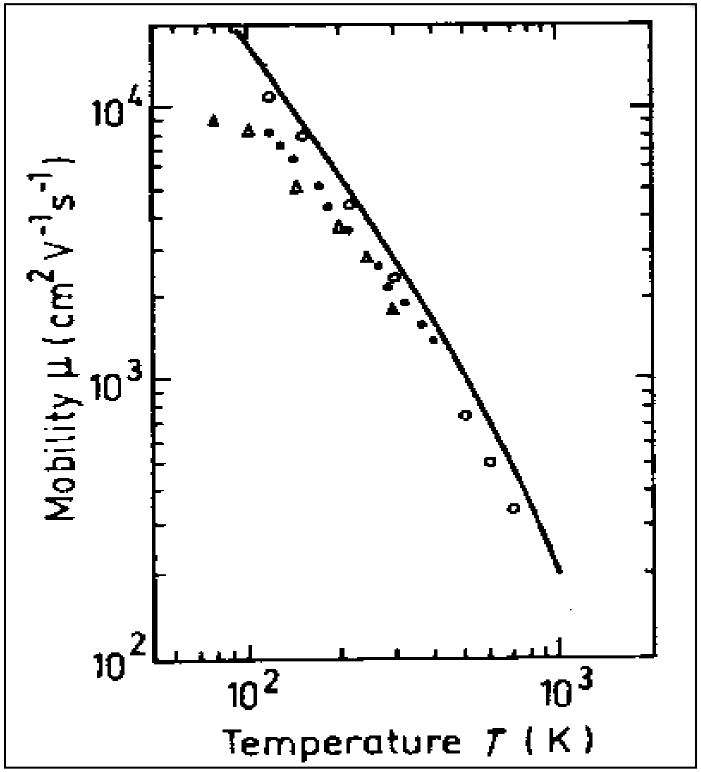


Nc ~ 10^20 cm-2
Nv ~ 10^19 cm-2
Ni ~ 10^-27 cm-2

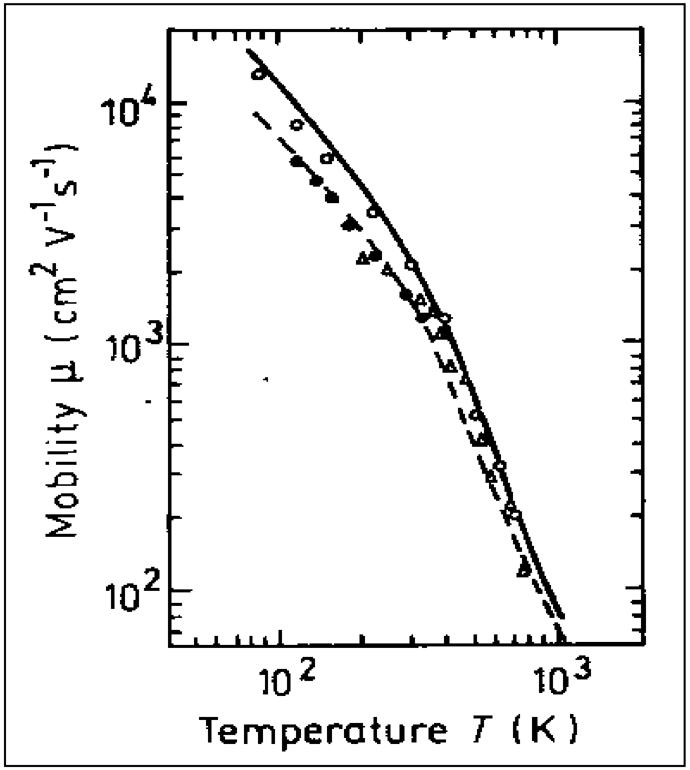
Band diagram depends in the crystal axes – anisotropy of parameters is expected

Mobility in natural diamond

electrons

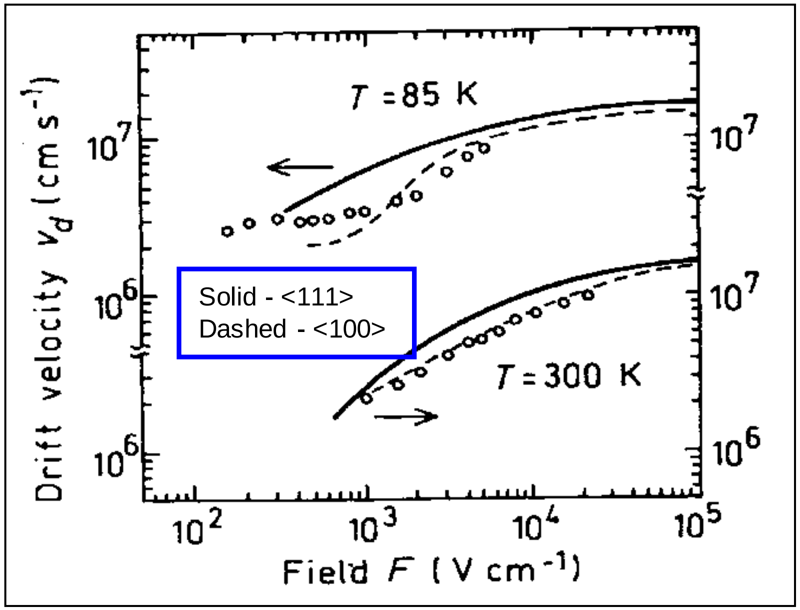


holes

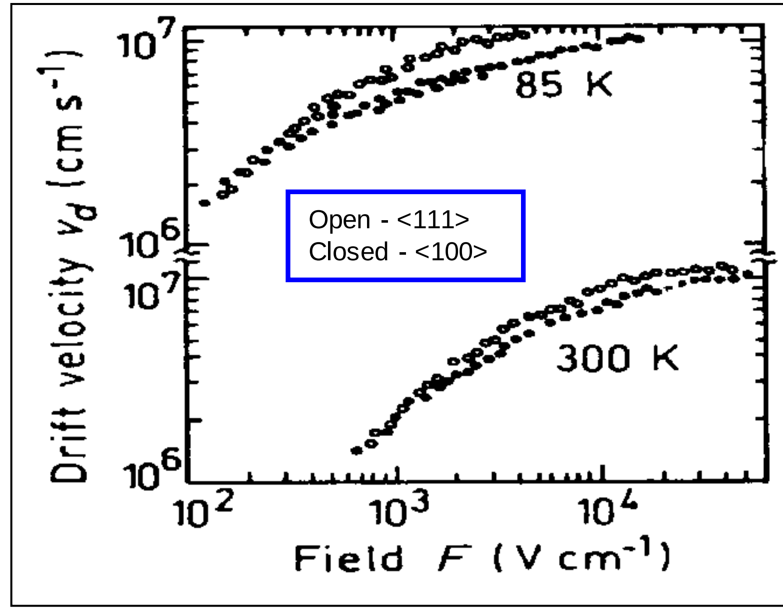


Anisotropy of drift velocity

electrons

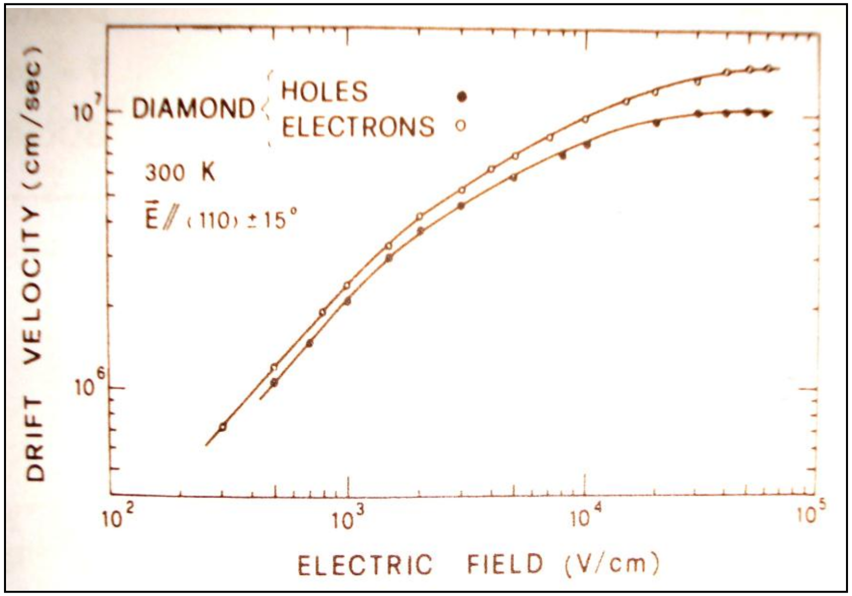


holes

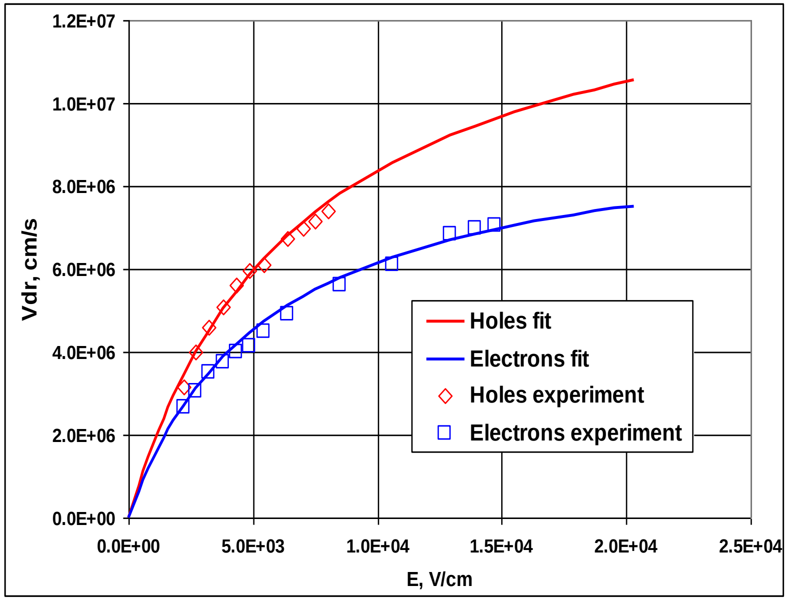


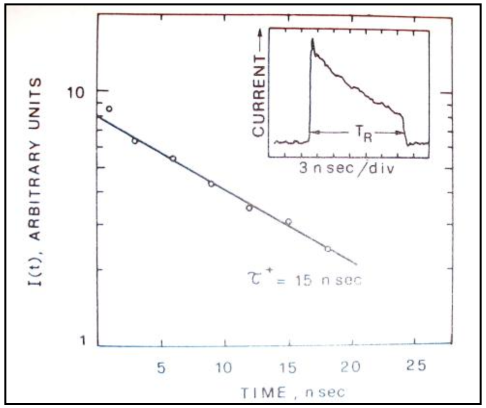
Drift velocity in modern Diamond

Natural



sc-CVD





	holes	electrons
mu0, cm/Vs	2100	2400
Vs, cm/s	1.05E+07	1.50E+07

	holes	electrons
µ0, cm/Vs	2064	1714
Vs, cm/s	1.41E+07	9.60E+06

From C.Canali, ……
NIM 160 (1979) p. 73-77

Vdr = µ0E/(1+µ0E/Vs)

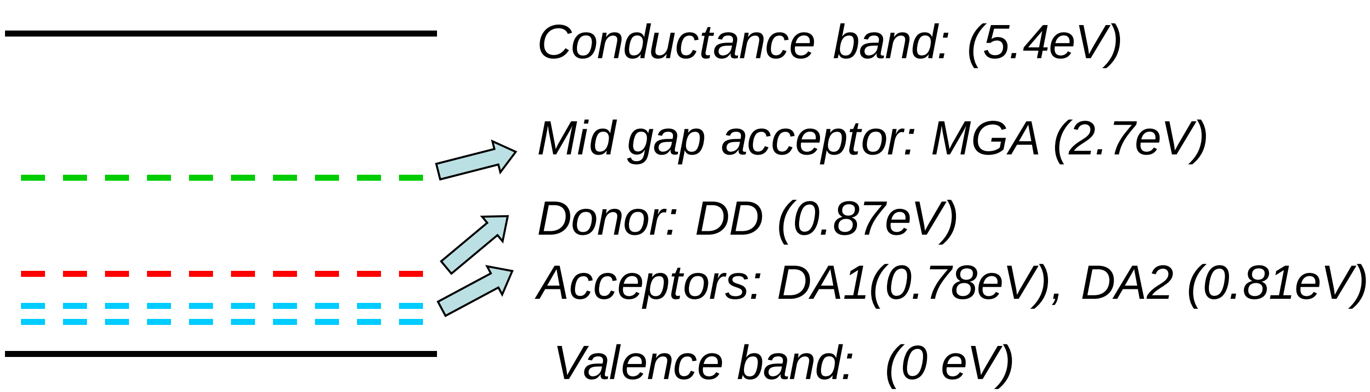
Effect of drift velocity anisotropy ???

Deep levels in CVD diamond

- INFN - Florence) model

  Proofed by :thermal stimulated current measurements – TSC and PICTS

  Photoconductivity measurements



What does this model define ??

Trends in the improvement of CVD diamond technology

DL's concentration

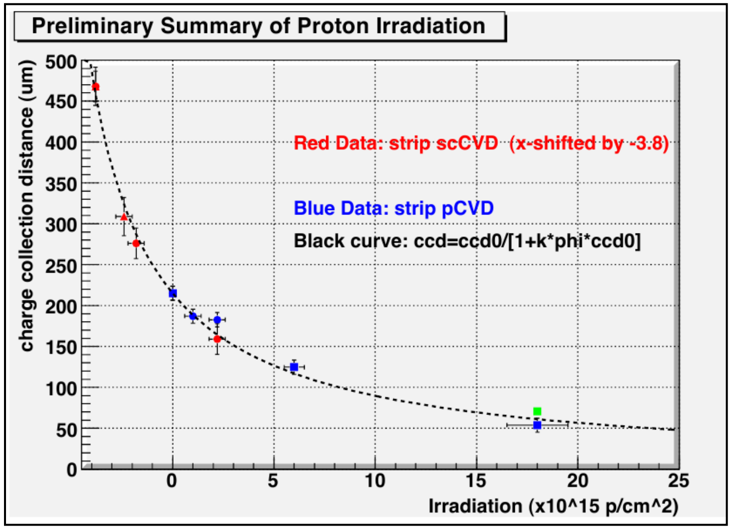
Years	**1998**	**2000**
MGA , cm-3	$5x10^{15}$	$2.5x10^{15}$
DD , cm-3	$5x10^{15}$	$2.5x10^{15}$
DA1 , cm-3	$3x10^{14}$	$4x10^{13}$
DA2 , cm-3	$6x10^{13}$	$2x10^{13}$

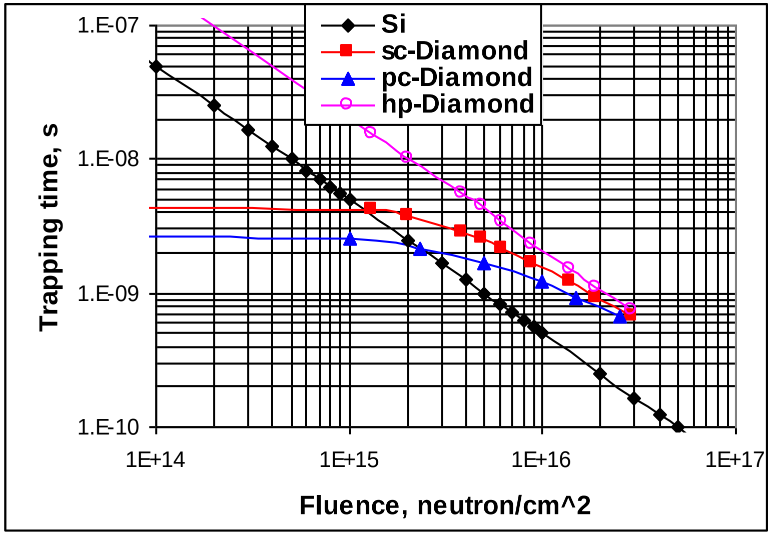
Bulk diamond parameters

E_f, eV	0.935	0.964
n, cm^{-3}	$1.84x10^{-57}$	$5.8x10^{-57}$
p, cm^{-3}	$8.61x10^{2}$	$2.68x10^{2}$
ρ, Ohm cm	$4x10^{12}$	$1.27x10^{13}$
$+N_{tr}$ (e), cm-3	$3.57x10^{14}$	$5.99x10^{13}$
$-N_{tr}$ (h), cm-3	$3.58x10^{14}$	$5.99x10^{13}$
N_{tr}eff, cm-3	$7.15x10^{14}$	$1.2x10^{14}$

- ***Diamond is a p-type semiconductor***
- ***Purification leads to:***
  - ✓Decrease of Fermi livel
  - ✓Increase of resistivity
  - ✓Increase of trapping

Trapping in irradiated Si and Diamond





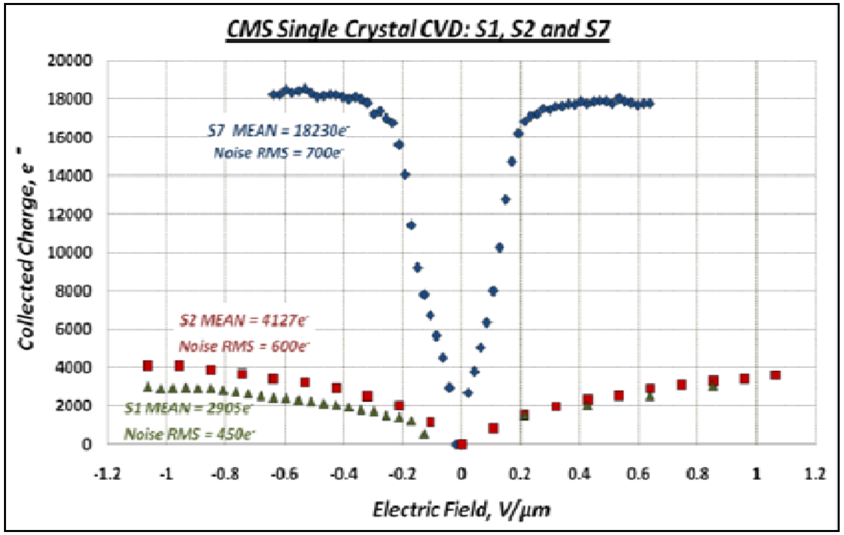
From:
W.Trischuk & RD42,
Resent advanses in diamond detectors

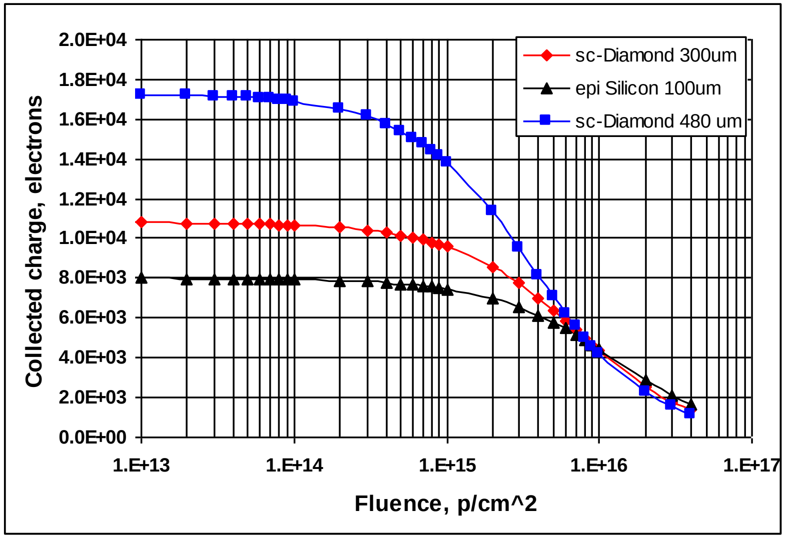
Conditions for comparison:
Electric field 1V/um
Diamond SC and PC
Silicon MC
Diamond irradiated by protons 24GeV
Silicon irradiated by protons 24GeV

Conclusion:
Trapping time degradation rate:
Silicon β = 2e-7 cm^2/s
Diamond β = 7.5e-7 cm^2/s

CCD = Vdr*τ
T ~ 1/Ntr
Ntr ~ F

Absolute signal
in Si and Diamond PAD detectors
(trapping time degradation effect)





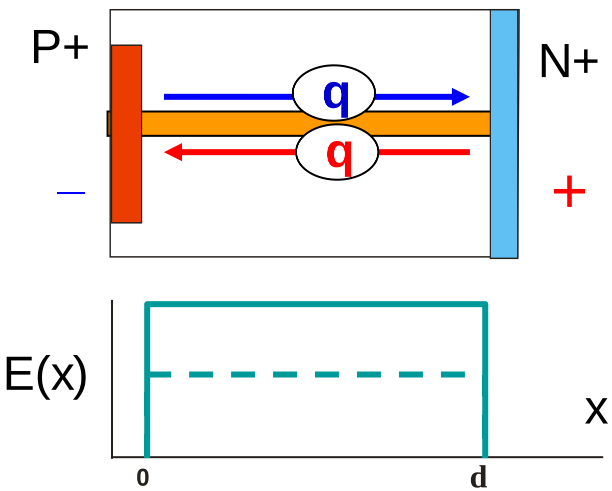
From "Fast beam conditions monitoring (BCM1F) for CMS" by N/Bernardino Rodriguess, …

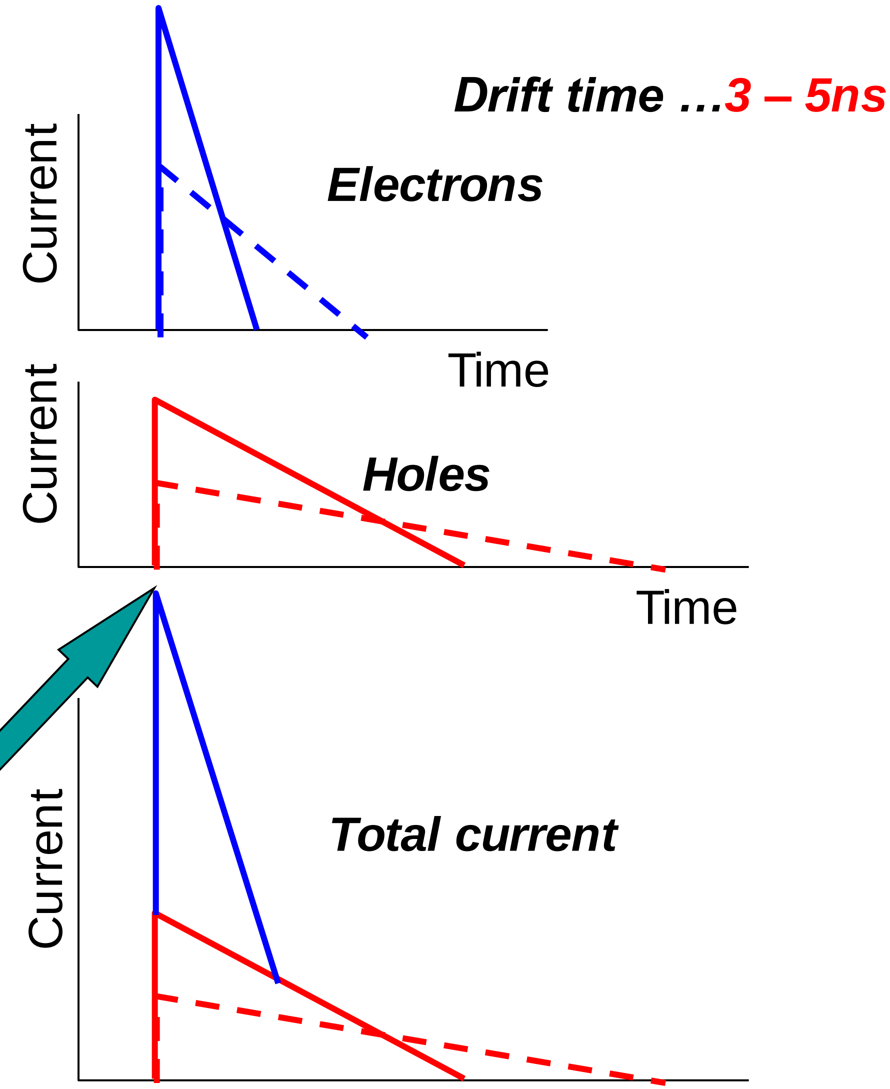
Vb = 300V

sc-Diamond, 480um
at Fp=1.75e15 1/cm2
Qcoll (S1) = 2900e and
Qcoll (S2) = 4130e !!!
Expected > 10000e

Parameters
Uniform electric field
temperature - 290K
d(1/tau)/dF silicon - 2e-7[s^-1*cm^2]
d(1/tau)/dF diamond - 7.5e-8[s^-1*cm^2]

Current response of pad semiconductor detector (MIPs)





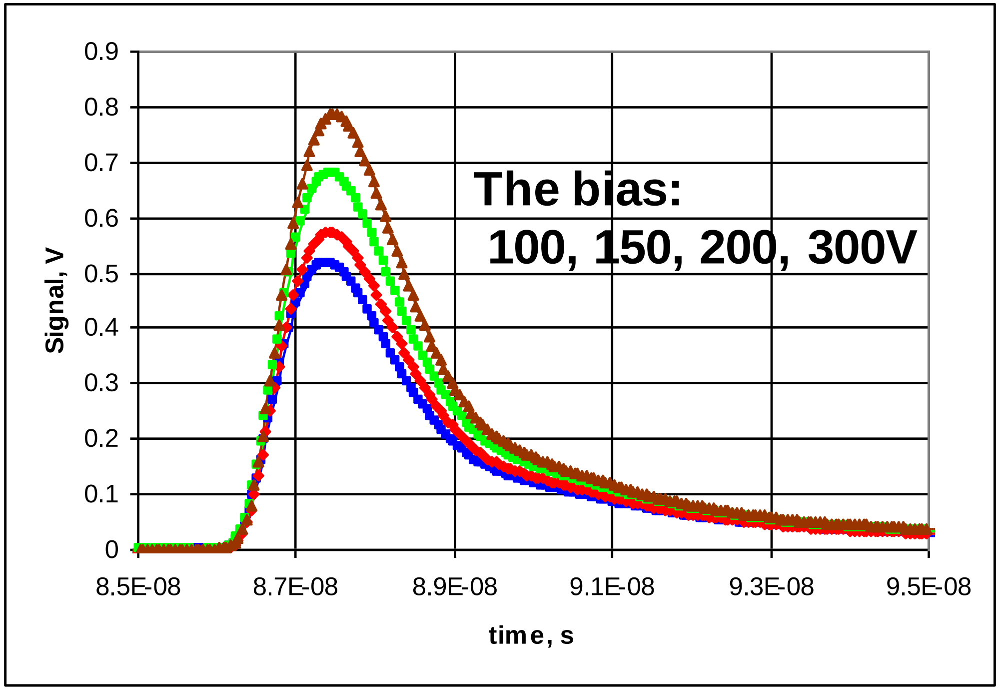
d ……300mkm
N_{eff} ….10^{11}cm^{-3}
V_{fd}….. <20 V
V_{op}……100-300V

$$J_{max} = 1/d\, q(Gd\mu_e E + Gd\mu_h E) = qG(\mu_e E + \mu_h E) = qG(\upsilon_e + \upsilon_h)$$

G – pair generation rate, 1/cm

V, Eremin, PTI, BLM, Oct 2011

MIP current response for Si detector



Detector thickness - 300 um
MIP detection (Laser 1060 nm)
Rise time - 600 ps (defined by electronics)
Expected time resolution <100 pc

Si and Diamond

Parameter		Silicon	pc-Diamond	sc-Diamond
Z		14	6	6
A		28.1	12	12
Density		2.329	3.515	3.515
Bend width, eV		1.12	5.48	5.48
Pair creation energy, eV		3.63	13.1	13.1
Permittivity		11.9	5.7	5.7
Resistivity, kOhm cm		<100	>1e10	>1e10
Drift mobility, cm^2/V/s	h	505	1000	2400
	e	1450	1800	1900
Saturation velocity, cm/s	h	8.4e6	1e7 ?	
	e	1e7	2e7 ?	
MIP pair generation density, cm-1		0.9e6	0.36e6	
MIP response amplitude, A		1.5e-6	1e-6	
Life/trapping time, ns		1e7	1 – 10	40
Charge collection distance, um		100000	< 200	> 500

Conclusions

1. Many physical parameters for Diamond are still not precisely defined: Vdr, mobility, Vs, trapping related parameters.

2. Shallow level impurities are not discovered for Diamond that makes impossible fabricate P-i-N structures.

3. Trapping time degradation is much less then for Silicon however the high density of defects and impurities limits the trapping time at the level equivalent of of flence >1e15 p/cm^2

4. Polarization could be a major unpredictable factor of Diamond detector operation in DC current mode at low temperatures.

Thank you for your attention